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# Recalibration of the Voyager PRA antenna for polarization sense measurement

**L. Wang and T.D. Carr**

Department of Astronomy, University of Florida, Gainesville, FL 32611, USA

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**Abstract.** The Voyager Planetary Radio Astronomy (PRA) antenna and receiver system provides an indication of the sense of elliptical or circular polarization of radiation that is not correct for all directions of incidence. The true sense could be determined for all directions if accurate calibration data were available. It was not feasible to make the calibration before the Voyagers were launched. Lecacheux & Ortega-Molina (1987), however, were able to derive such calibration data from planetary radio observations made in flight. They expressed their results in terms of the tilt of a plane (the E-plane) that divides the incident ray directions for which the indicated polarization sense is correct from those directions for which the indicated sense is reversed. We demonstrate that there are certain directions for which this calibration is itself in error, and that the surface dividing the two sets of incident rays is more complex than a tilted plane. We are able to make a crude approximation to the true surface from the limited data available.

**Key words:** Voyager – giant planets – radiometer – polarization

## 1. Introduction

The passage of Voyager 2 by Neptune in late August 1989 marked the end of an amazingly successful program of exploration of the outer planets. During the missions of the two Voyagers, the Planetary Radio Astronomy (PRA) measurement system recorded spectral intensity distributions of low frequency radio emissions from Jupiter, Saturn, Uranus, and Neptune. The PRA observations yielded a huge amount of data which has been and will long continue to be of great importance in developing an understanding of source locations and beaming geometry, emission mechanisms, and relationships of the radio sources to their magnetospheric environments. The PRA data bank is an invaluable scientific resource. It may remain the only such data we have for decades to come, particularly in the case of Uranus and Neptune.

*Send offprint requests to*: L. Wang

Primary goals of the Voyager PRA experiment were to locate the radio sources, to determine their emission beaming patterns, and to ascertain the magnetoionic mode of the radiation. These goals have thus far been achieved only to a limited extent. The antenna was not designed for direction finding. Since the spacecraft was three-axis stabilized, the antenna beam could not execute the repeated scans across the source that might have provided direction information. However, in the vicinity of each planet the spacecraft was occasionally made to execute a complete or partial rotation in a relatively short time, usually causing the antenna beam to be scanned once across the source direction. Although the moving antenna beam in such cases was much too broad to produce a sufficiently sharp pattern of intensity modulation of the received radiation from which useful source directional information could be derived, the sweeping of the electric plane of the antenna system across a source direction sometimes produced a relatively abrupt reversal of the indicated sense of elliptical polarization. (The electric plane, or "E-plane", of an antenna is that plane upon which is projected the component of the incident-wave electric field vector that is effective in exciting the antenna, and in the present case is also the plane dividing the directions of incident rays for which the indicated elliptical polarization sense is correct from those for which it is reversed.) Measurements have previously been made of the antenna E-plane orientation relative to the spacecraft as deduced from the observed times of occurrence of polarization reversals during roll maneuvers, using an assumed location of the calibration source (which was at Saturn in some cases and at Uranus in others) (Ortega-Molina & Daigne 1984; Lecacheux & Ortega-Molina 1987; Ortega-Molina & Lecacheux 1990; Sawyer et al. 1991). In this paper we demonstrate that when the best of these previous E-plane orientation calibrations are used to obtain directional information from other sources, impossible results can be obtained. From previously unused roll-maneuver observations of a Jovian source made under particularly favorable conditions, we derive a corrected value of the relative orientation of the antenna E-plane which is much different from the currently accepted value. We subsequently made other (less accurate) determinations from observations obtained during other spacecraft rotation-maneuvers, however, that suggest that the tilt of an assumed antenna E-plane is different when the source is to the rear of the plane formed by the PRA orthogonal monopole pair than it is when the source is forward of this plane. We conclude that the actual "E-surface" can best be approximated by a pair of intersecting planes, to be used separately for sources in front of the monopole plane and those behind it, respectively. We provide calibration data in the form of the tilt angles of the effective E-plane as a function of the azimuth of the source (in the antenna monopole coordinate system). We expect that our new calibration data will make possible the correction of previous erroneous conclusions regarding the true polarization sense of a significant amount of the radiation received by the Voyagers from Jupiter, Saturn, Uranus, and Neptune from direction angles greater than 45° with respect to the normal to the monopole antenna plane.

## 2. Polarization response of the PRA antenna

The identical Planetary Radio Astronomy (PRA) radiometers on board the two Voyagers were designed to receive whatever decametric, hectometric, or kilometric radio signals might be observed from the vicinity of each of the radio planets Jupiter, Saturn, Uranus, and Neptune (Warwick et al.1977; Lang & Peltzer 1977). The radiometer consists of an orthogonal pair of 10-m monopoles connected to a stepped-frequency receiver covering the range 1.2 kHz to 40.2 MHz. The signals from the two monopoles are added in phase quadrature by means of two switchable quarter-wave hybrids, alternately sending left hand (LH) and right hand (RH) elliptical intensity components of the observed radiation to the receiver. We define the apparent polarization ratio as the quantity $(L-R)/(L+R)$, where $L$ and $R$ are the indicated LH and RH intensity outputs of the receiver (non-planetary background having been subtracted out). Ideally, if the two monopoles together with the spacecraft body were equivalent to a pair of orthogonal dipoles in free space and if a source being observed were located in the positive direction of the axis perpendicular to the two dipoles, the indicated RH and LH receiver outputs (background-subtracted) would actually be the RH and LH circularly polarized intensity components of the radiation, and the apparent polarization ratio would be the true degree of circular polarization. The sources that were actually observed, however, were nearly always considerably offset from the axis perpendicular to the equivalent dipoles. Furthermore, unwanted coupling between the two monopoles due to the other structures projecting from the spacecraft will result in a certain amount of contamination of both the RH and LH outputs. Thus the measured Voyager RH and LH elliptically polarized intensity components uniquely define neither the polarization ellipse of the incident radiation nor its true RH and LH circularly polarized intensity components. The only Voyager polarization measurement that can be made unambiguously is the sense of elliptical or circular polarization, and this only if it is known on which side of the E-plane the source lies. The indicated sense becomes incorrect when a source direction crosses the E-plane in passing to the back side. That is, the sign of the apparent polarization ratio is opposite from that of the true degree of circular polarization on the back side of the antenna E-plane, but is correct on the front side.

There were actually two receivers on each spacecraft, for the lower and higher frequency ranges, respectively. The low-band receiver had 70 channels of 1.0 kHz bandwidth each, with center frequencies spaced at 19.2 kHz intervals from 1.2 kHz to 1326 kHz. The high-band receiver consisted of 128 channels of 200 kHz bandwidth each, with center frequencies spaced at 307.2 kHz intervals from 1.2 MHz to 40.4 MHz. The high-band receiver was designed especially for the observation of Jovian decametric radio emissions. The PRA radiometer was usually operated routinely in the so-called POLLO sweeping mode, in which all 198 frequency channels of the high- and low-band receivers together were swept in 6 sec, dwelling at each channel for 25 msec. From one step to the next in the channel switching sequence, the antenna polarization sense was reversed, i.e., was changed from RH to LH or vice versa. Thus the time required for making a measurement of both the RH and LH intensity components at both senses of elliptical polarization at a given frequency was 12 sec. The data used in the present paper consisted of successive averages of 4 pairs of RH and LH intensity measurements, each average spanning an interval of 48 sec.

The two orthogonal 10-meter monopoles are insulated from the spacecraft body. As previously indicated, each monopole together with the spacecraft body, including its projecting structures, acts as a dipole. Since each monopole resonates as a quarter-wave element at about 7.5 MHz, it and the spacecraft body together behave more or less like a free-space half-wave dipole in the vicinity of this frequency. Thus for all frequency channels of the low-band receiver, i.e., at 1326 kHz and below, the equivalent dipole corresponding to each monopole has approximately the "short dipole" frequency-independent directional E-field pattern (for which the field strength of a transmitted signal at a fixed distance is proportional to the sine of the direction angle with respect to the dipole). The longest of the projecting structural features of the spacecraft body is the 13-meter magnetometer boom, which is perpendicular to both monopoles. The spacecraft is approximately bilaterally symmetrical about the plane that contains the magnetometer boom and bisects the 90° angle between the two monopoles. The aperture plane of the paraboloidal telemetry dish (3.7 m in diameter) is perpendicular to the symmetry plane.

The relevant coordinate systems are shown in Fig. 1. The Voyager structural geometry is also illustrated in figures in Warwick et al. (1977) and Ortega-Molina & Daigne (1984). In the spacecraft coordinate system, $[X, Y, Z]$, the $Y$ axis lies along the intersection of the symmetry and dish aperture planes, its positive direction being the one which is farther from the magnetometer boom. (The boom supporting the instrumentation platform extends about 4.5 m approximately in the positive $Y$-axis direction, and the nuclear-electric power supply boom extends about the same distance in the opposite direction; these features are not indicated in the figure.) The $Z$ axis is perpendicular to the dish aperture plane, its positive direction being the farther one from the magnetometer boom. This coordinate system is

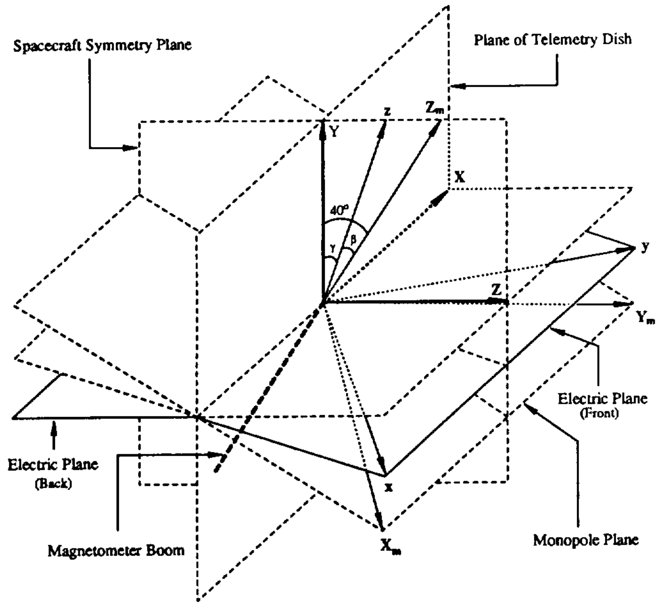


**Fig. 1.** Coordinate systems used in the PRA experiment on board the Voyager spacecraft. The $X_{\mathrm{m}}$ and $Y_{\mathrm{m}}$ axes correspond to the directions of two monopoles, and the negative direction of the $Z_{\mathrm{m}}$ axis is that of the magnetometer boom

used in the Voyager SEDR (Supplementary Experimental Data Record) ephemeris files for expressing spacecraft-centered positions and directions. In the PRA antenna coordinate system, $[X_{\mathrm{m}}, Y_{\mathrm{m}}, Z_{\mathrm{m}}]$, the $X_{\mathrm{m}}$ and $Y_{\mathrm{m}}$ axes are defined by the directions of the two monopoles, and the negative direction of the $Z_{\mathrm{m}}$ axis is that of the magnetometer boom.

Unfortunately, it did not prove feasible to measure the directional and polarization characteristics of the PRA antenna system prior to the Voyager launchings. However, while the system was under development, Sayre (1976) approximated its directional characteristics at frequencies of 0.25, 0.5, and 2.5 MHz by numerical modeling, simulating the shape of the spacecraft body and its projecting structures. Sayre's report, which was not published, contains PRA antenna directional patterns that are relevant to our investigation. These plots have apparently not been used in related investigations, except for being briefly mentioned by Ortega-Molina & Daigne (1984). We reproduce in Fig. 2 Sayre's unpublished Voyager PRA antenna directional E-field patterns at 0.5 MHz for the $X_{\mathrm{m}}$ monopole (in combination with the spacecraft body) in the $X_{\mathrm{m}}Z_{\mathrm{m}}$ and $Y_{\mathrm{m}}Z_{\mathrm{m}}$ planes, and also for the $Y_{\mathrm{m}}$ monopole in these two planes. The sharply defined diametrically opposite minima in each of these patterns are in the directions closest to the line along which the equivalent dipole lies. The following information can be deduced from the plots of Fig. 2:

- Each monopole pattern is approximately that of a short dipole which is tilted from the monopole direction, the dipole centers being approximately at the intersection of the two monopoles.
- The two equivalent dipoles are not perpendicular, but intersect in the present case at a angle of about 137°; this intersection angle is bisected by the spacecraft symmetry plane.
- The normal to the plane (on its "front" or positive side) that is defined by the two equivalent dipoles lies within a degree of the spacecraft symmetry plane, and is tilted 55° from the normal to the monopoles, in the direction away from the telemetry dish aperture plane.

In Fig. 1, the orientation of the $[x, y, z]$ coordinate system is determined by that of the assumed equivalent crossed free space dipoles, which are not necessarily orthogonal. These dipoles, the positive half of each of which is indicated by a dotted line in the figure, determine the $xy$ plane. The dipole nearest the $x$ axis will be referred to as the $x$ equivalent dipole, and that nearest the $y$ axis as the y dipole. They correspond respectively to the $X_{\mathrm{m}}$ and $Y_{\mathrm{m}}$ monopoles. The $x$ and $y$ axes are symmetrical about the spacecraft symmetry plane, as are the $x$ and $y$ equivalent dipoles. The angle of intersection of the E-plane ($xy$) with the monopole plane ($X_{\mathrm{m}}Y_{\mathrm{m}}$) is $\beta$, as is the intersection angle of the $z$ axis with the $Z_{\mathrm{m}}$ axis. The direction of a radio source can be expressed by the colatitude and azimuth with respect to either the $[X_{\mathrm{m}}, Y_{\mathrm{m}}, Z_{\mathrm{m}}]$ system or the $[x, y, z]$ system. Transformation from the $[X_{\mathrm{m}}, Y_{\mathrm{m}}, Z_{\mathrm{m}}]$ system to the $[x, y, z]$ system can be done through the matrix **M**:

$$\mathbf{M} = R_3\left(-45^\circ\right)\ R_2\left(-\beta\right)\ R_3\left(45^\circ\right)$$

where $R_2$ and $R_3$, which are rotation matrices about the $y$ and $z$ axes, are expressed as:

$$R_2(\alpha) = \begin{pmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix},$$

$$R_3(\alpha) = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Ortega-Molina & Daigne (1984) developed an analytical model of the Voyager PRA antenna system, based on equivalent tilted and not necessarily orthogonal crossed dipoles. Leblanc & Daigne (1984), Lecacheux & Ortega-Molina (1987), and Leblanc et al. (1987) identified a number of instances of purely instrumental polarization reversals that occurred during roll maneuvers when radiation was being received from Jupiter, Saturn, and Uranus. Although it had long been known that a reversal of the indicated sense of polarization would occur if the antenna E-plane swept across an elliptically or circularly polarized source, the first quantitative demonstration of such instrumental reversals (and the first actual measurement of the relative orientation of the E-plane) was provided by Lecacheux & Ortega-Molina (1987). They found from the analysis of a set of such events that had been observed with the low-band receiver channels during the Saturn and Uranus encounters that regardless of the initial state of polarization of the radiation, the instrument has a null-polarization response for a set of source directions that lie approximately within a plane. In each case the polarization sense

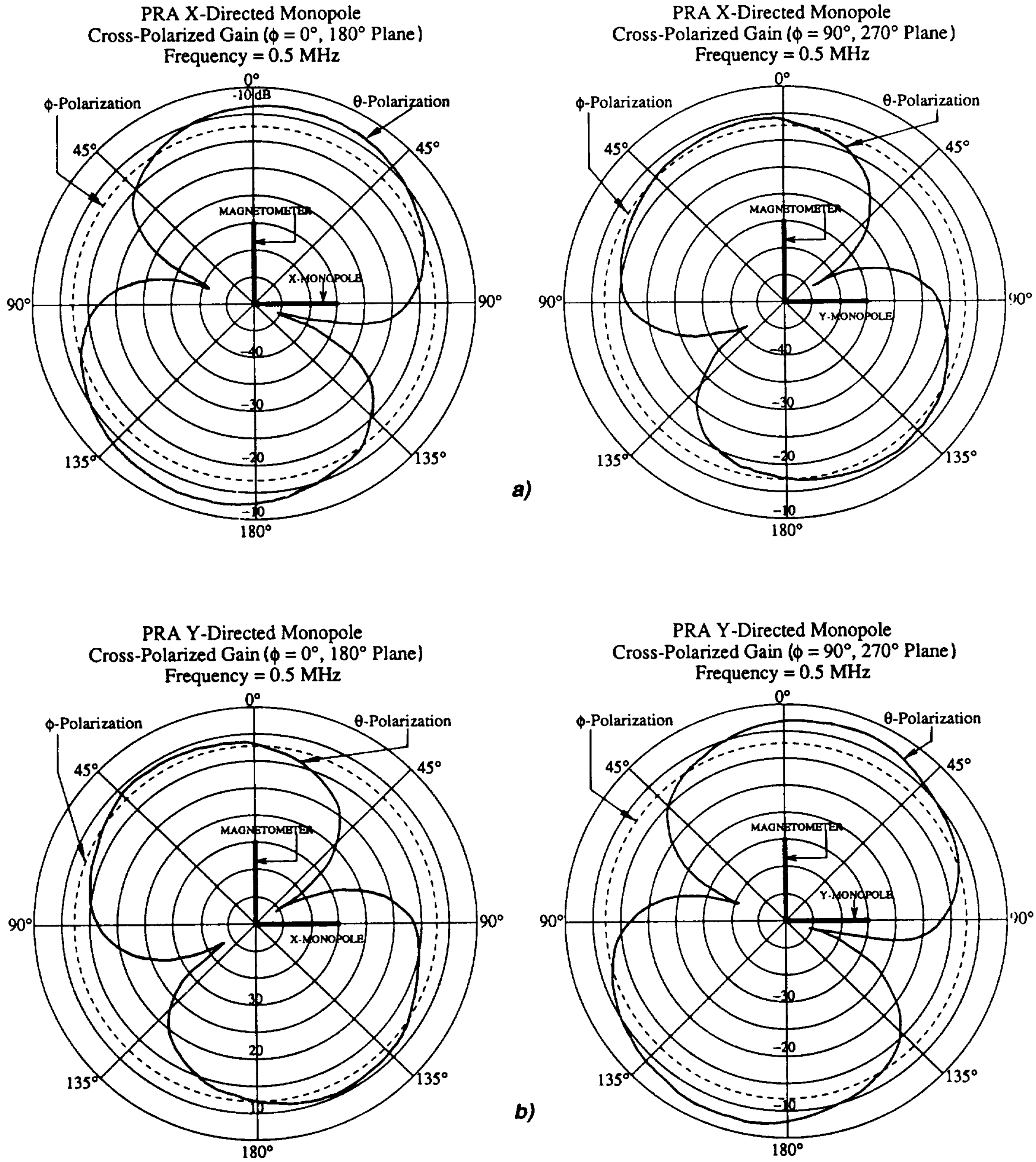


**Fig. 2. a and b.** The PRA antenna directional patterns at 0.5 MHz for the $X_m$ monopole in the $X_m Z_m$ and $Y_m Z_m$ planes **a**, and for the $Y_m$ monopole in these two planes **b**, reproduced from a numerical simulation modeling by Sayre (1976)

became reversed from its initial sense as the plane was crossed by the source direction vector. They interpreted this plane as the E-plane of the equivalent crossed short dipoles. Assuming the Saturnian source to be located as proposed by Kaiser & Desch (1982), which was later confirmed by Lacacheux & Genova (1983), and the Uranian source to be located at the center of the planet, they calculated the approximate orientation of the E-plane in the coordinate system of the spacecraft. They found the E-plane tilt angle $\beta$ in Fig. 2 to be about 23°3 and the equivalent dipole intersection angle to be $90° \pm 10°$. We note that this value of $\beta$ is less than half that found by Sayre, but that our initial and most accurately determined value, to be presented below, is in general agreement with Sayre's.

Ortega-Molina & Lecacheux (1990) deduced from a combined analytical study and statistical investigation of a considerable amount of kilometric radiation data from Saturn that the equivalent dipole intersection angle is 82°6 ± 1°8. Their method required the assumption that the Saturnian kilometric radiation is always 100 percent circularly polarized, in opposite senses for two assumed polar sources. They presented evidence that this assumption is correct. In their analysis, the E-plane tilt angle $\beta$ could not be measured. There is a large difference in the Ortega-Molina and Sayre values of the equivalent dipole intersection angle.

Ortega-Molina & Lecacheux (1991) and Pedersen et al. (1992) have subsequently attempted to use the foregoing E-plane orientation calibration data to deduce source location information from roll-maneuver polarization-reversal events occurring during the Jupiter and Neptune encounters. As we have stated previously, however, we will demonstrate that the directional calibration used by these investigators can lead to impossible results. We attribute this to their use of roll-maneuver polarization reversal (referred to as RMPR hereafter) events for the E-plane calibration that did not meet the selection criteria that we outline below.

## 3. Antenna E-plane calibration for sources in a particular azimuth region

### *3.1. Choosing optimum roll-maneuver polarization reversal events*

We have initially attempted to recalibrate the relative orientation of the PRA antenna E-plane using particularly favorable and previously unused RMPR events that occurred near Jupiter. For these events we were able to derive enough independent information about the magnetospheric location of the source that their offset from the center of the planet could be estimated with the required accuracy. (The SEDR ephemeris tape provided precise locations of the center of the planet at regular intervals.) In choosing suitable RMPR events with which to make the calibration, the following conditions were favored: *i*) the ratio of the intensity of the received radiation to the spacecraft background noise level must be relatively high; *ii*) the received radiation must have a relatively high degree of circular polarization; *iii*) the geometry must be such that the spacecraft roll maneuver

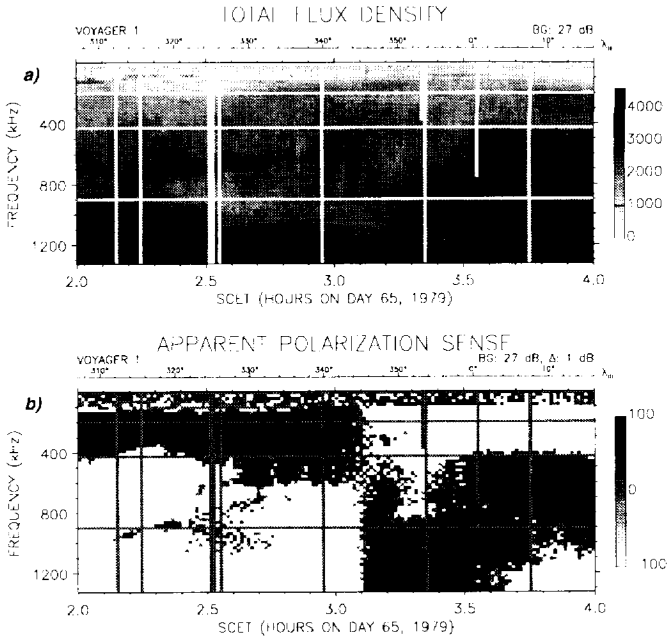


**Fig. 3. a and b.** A roll-maneuver polarization reversal (RMPR) event recorded by the Voyager PRA experiment in the low-frequency-band channels on March 6, 1979. Panel **a** is the total flux density as a function of time and frequency, with darker shades of gray indicating higher intensities. Panel **b** indicates the apparent sense of elliptical or circular polarization as a function of time and frequency, with the LH sense represented by black and the RH by white; gray regions are for other cases

produces large changes in the angle between the radius vector to the planet and the antenna E-plane both before and after this angle passes through zero; *iv*) the radiation must have been emitted from only one source, as indicated by the uniqueness and sharpness of the transition from the initial apparent polarization sense to the opposite one, and the uniformity of this reversal over a wide range of frequencies. During the Voyager flybys of Jupiter, Saturn, Uranus, and Neptune many roll maneuvers were made, but we found only a few of them that satisfy the above criteria. The three best events for E-plane calibration took place during the encounter with Jupiter; they are the ones upon which our initial calculations are based.

### *3.2. Initial E-Plane calibration from three selected events*

The best of the three above-mentioned RMPR events was a near-perfect one that occurred between about 02:54 and 03:19 SCET (spacecraft event time) on March 6 (day 65), 1979, when Voyager 1 was about 15 $R_J$ ($1 R_J = 71,372$ km) from Jupiter's center. It is illustrated in Fig. 3. Panel *a* shows the total intensity as a function of time and frequency (darker shades of gray indicate higher intensities). Panel *b* indicates the apparent sense of elliptical polarization as a function of time and frequency. In this panel the polarization sense as indicated by the PRA receiver is left-handed in the black regions and right-handed in the white regions. Gray regions can indicate linearly polar-

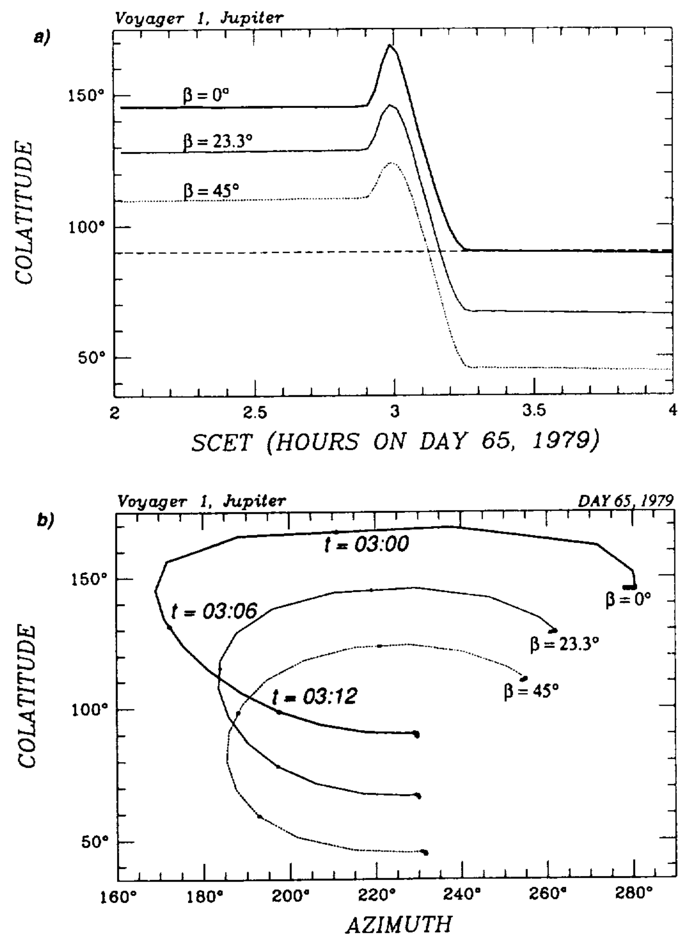


**Fig. 4. a** Colatitude of the center of Jupiter with respect to the positive normal to each of three planes associated with the PRA antenna, as a function of Spacecraft Event Time (SCET) during the RMPR event of Fig. 3. The indicated values of $\beta$ are the tilt angles of the three planes from the monopole plane, for which $\beta = 0°$ (see Fig. 1). **b)** The above colatitudes have been replotted as functions of the azimuths about the respective positive normals to the above three planes; the symmetry plane lies at 45° azimuth in each case

ized radiation, unpolarized radiation (not believed to occur in the Voyager data), no radiation at all, or radiation having two components (from separate sources) of approximately equal intensities and axial ratios but opposite senses of elliptical or circular polarization. During the roll maneuver, Jupiter's direction angle in the monopole coordinate system $[X_m Y_m Z_m]$ changed more than 70° in colatitude and more than 100° in longitude. Fig. 4a shows the time variation of the colatitude of Jupiter's center as expressed in the equivalent-dipole coordinate system $[xyz]$ for each of three assumed values of the tilt angle $\beta$ of the $xy$ plane (E-plane) with respect to the $X_m Y_m$ plane (monopole plane). The upper curve, for $\beta = 0°$, is the one that would apply if the E-plane coincided with the monopole plane. The middle curve should be used if $\beta = 23.3°$ as found by Lecacheux & Ortega-Molina (1987). The lower curve is applicable if our value of $\beta$ calculated below, 45°, is the correct one. It is apparent that before the roll maneuver began, Jupiter's center and also all possible positions of the radio source were far south of the assumed E-plane for each of the curves. Thus at every frequency in Fig. 3b the indicated polarization sense was opposite to the true sense before the maneuver began, but was correct after the maneuver. We can rule out the $\beta = 0°$ curve without consideration of the actual source location relative to Jupiter's center. For any reasonable assumed offset of the source from the center of the planet the polarization sense reversal as indicated in Fig. 4a for $\beta = 0°$ would have been marginal if it had occurred at all, whereas the actual reversal shown in the figure is not at all marginal. The three curves in Fig. 4b are plots of colatitude (from the $Z_m$ axis) as a function of azimuth (in the $X_m Y_m$ plane) for the $\beta$ values 0°, 23.3°, and 45°. It is apparent that for the $\beta$ values 23.3° and 45° the azimuths at which the polarization reversals take place (i.e., at which the curves cross $\theta = 90°$) differ by only 10°, and the times of the reversals differ by slightly more than a minute.

The event displayed in Fig. 3 clearly demonstrates that the lower limit of Jupiter's predominantly hectometric component can be as low as 100 kHz, extending deep into the kilometric band. It also shows that there is an actual reversal of polarization sense with frequency near 500 kHz. The true polarization sense was LH for frequencies above a somewhat variable boundary in the vicinity of 500 kHz and was RH for frequencies below this boundary. The spacecraft was in the southern Jovian magnetic hemisphere at the time of the event. If we make the usual assumption that the radiation is emitted in the X mode simultaneously from magnetically conjugate sources in opposite auroral zones, and we assume that in this case the contribution of the nearer southern hemisphere source to the received radiation was greater than that of the northern source, then the observed polarization sense at frequencies above about 500 kHz is correctly explained. Two possible explanations of the reversed polarization sense below 500 kHz are that (*a*) although the emission from the conjugate sources is still in the X mode, the frequency dependence of their emission beams has caused the intensity contribution from the northern source to exceed that from the southern one despite the latter being the closer, or (*b*) the lower-frequency emission from the two conjugate sources was predominantly in the O mode. We are not concerned in this paper with the true polarization sense of radiation at frequencies less than 500 kHz.

Figure 3 clearly shows that the reversal of the apparent polarization sense at most frequencies between 100 and 1300 kHz occurred simultaneously to within one 48-sec pixel width. The reversal time was 03:06 SCET. If the source were located at the position of the center of the planet, the polarization reversal times for assumed E-plane tilts of 23.3° and 45° would be the times at which the corresponding curves cross the 90° colatitude line in Fig. 3a. Although the fact that the $\beta = 23.3°$ curve crosses this line considerably after 03:06 SCET suggests that this value of the E-plane tilt angle is unrealistic, such a conclusion is not yet justified because the effect of the offset of the true source position from the center of the planet has not been taken into consideration. However, Fig. 5 shows clearly that this is indeed the case. The four oval-shaped curves in Fig. 5 represent

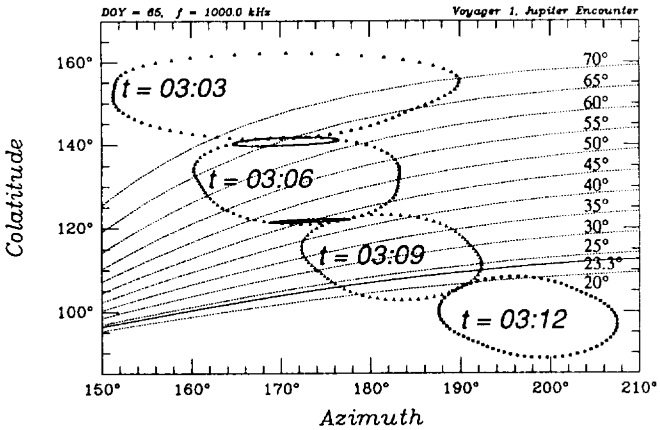


**Fig. 5.** Colatitude vs azimuth (in the monopole antenna coordinate system) for the radio horizons at 1 MHz as seen from the spacecraft (zero refraction assumed) at SCETs of 03:03, 03:06, 03:09 and 03:12, respectively, on day 65 of 1979. The finely dotted curves indicate the possible directions of arrival of rays lying within assumed antenna E-planes having the indicated tilt angles, in 5° increments. The two thick solid-line curves near the top and bottom of the radio horizon at the time of the apparent polarization reversal (03:06 SCET) represent the directions of all points along two possible conjugate source regions at the northern (lower) and southern (upper) intersections of the $L$ = 20 magnetic shell with the 1 MHz $f_c$ surface

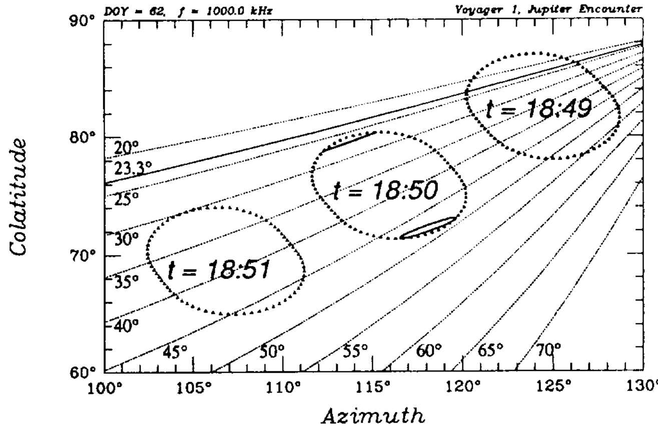


**Fig. 6.** Three ovals representing colatitude vs azimuth (in the monopole antenna coordinate system) for the radio horizons at 1 MHz for SCETs of 18:49, 18:50, and 18:51 on day 62 of 1979. The two solid-line curves near the top and bottom of the middle oval (at $t$ = 18:50, the time nearest the RMPR event) represent the directions of all points along two possible conjugate source regions at the northern (lower) and southern (upper) intersections of the $L$ = 20 magnetic shell with the 1 MHz $f_c$ surface

the colatitude of the radio horizon as a function of azimuth (in the monopole coordinate system) at a frequency of 1000 kHz as seen from the spacecraft at the SCET times 03:03, 03:06, 03:09, and 03:12, respectively. By radio horizon we mean the set of directions of the locus of the points of tangency of the straight lines from the spacecraft to the surface at which the electron cyclotron frequency equals the frequency of observation. (Our ray tracing investigations have indicated that refraction of rays penetrating the Io plasma torus can be neglected at the relatively high frequency of 1000 kHz; straight-line propagation can be assumed in this case.) The OTD magnetic field model was used in the horizon calculations. At a given time the points representing the directions of the radio source at 1000 kHz must lie on or inside the corresponding horizon oval. The dotted curves intersecting the ovals are plots of colatitude vs azimuth for assumed E-planes having tilt angles $\beta$ (from the monopole plane) in 5° increments. The thin solid curve at $\beta$ = 23°.3 represents the E-plane as determined by Lecacheux and Ortega-Molina; we shall hereafter refer to it as the L-OM E-plane. It is obvious that at the time of the apparent polarization reversal (03:06 SCET), all possible source regions intersected by the extended L-OM E-plane were beyond the radio horizon. At this time the lower edge of the horizon oval was still 20° below the L-OM E-plane. If this had been the true E-plane, it would have taken another 2 to 4 min for the reversal to occur. (Our mean timing error is less than 24 sec, i.e., half the interval between the Voyager data points.) Fig. 5 indicates that the true E-plane was tilted at least 43° from the monopole plane.

It is generally believed that the Jovian HOM sources are located within magnetically conjugate regions in the two auroral zones having L-shell values of approximately 10 to 20, at altitudes at which the electron cyclotron frequency ($f_c$) is nearly equal to the wave frequency (Carr & Wang 1989; Carr & Wang 1990; Ladreiter & Leblanc 1989; Ladreiter & Leblanc 1990; Barrow 1991). The extent to which these sources are distributed in magnetic longitude is still in question; they may extend around the full 360° or they may be limited to a sector of longitude. We have plotted in Fig. 5 for the time of the apparent polarization reversal (03:06 SCET) two closed (thick) solid-line curves representing the directions of all points in the two possible source regions along the northern and southern intersections of the $L$ = 20 magnetic shell with the 1000-kHz $f_c$ surface. On the basis of the oval-like curves in Fig. 5 alone we can state that ($a$) the $\beta$ value for the true E-plane is between 42° and 48° if the source was in the southern hemisphere; ($b$) the true $\beta$ is between 62° and 67° if the source was in the northern hemisphere, and ($c$) the L-OM $\beta$ value 23°.3 defines a plane that passes no closer than 23° from the southern hemisphere source (the nearer one). From the solid curves superimposed on the oval for 03:06 SCET we can decide in which hemisphere the source was located. Since the true polarization sense was LH at the time of the reversal of the apparent polarization, the predominant source region must have been the southern-hemisphere one (lower curve). Thus, on the basis of our best RMPR event alone, we would have concluded that the E-plane tilt, $\beta$, was 45° ± 3°. This is twice the L-OM value, but agrees more closely with the value deduced from Sayre's numerical modeling results shown in Fig. 2.

Next, we made similar calculations of $\beta$ from each of the other two of the three best RMPR events, for which the planet-to-spacecraft distances were 35 $R_J$ and 60 $R_J$, respectively. Fig. 6 shows three ovals representing the radio horizon directions at the time ($t$ = 18:50) of the 35 $R_J$ event and also at times one minute earlier and one minute later. Superimposed on the $t$ = 18:50 oval are the possible source points along the northern (lower) and southern (upper) intersections of the $L = 20$ magnetic shell with the 1000 kHz $f_c$-surface. Since the true polarization sense for this event was LH, the source must have been on the upper curve. The corresponding $\beta$ value is 27° ± 2°. Corresponding plots for the 60 $R_J$ event are very similar in appearance to those for 35 $R_J$, and also give 27° ± 1° for $\beta$. We believe that the apparent large discrepancy between this pair of $\beta$ values at 27° and the previous value of 45° was not due to measurement error, but instead is an indication that the assumption of a single E-plane for source directions at all azimuths about the antenna is an oversimplification. This is bourne out by the results presented in the next section.

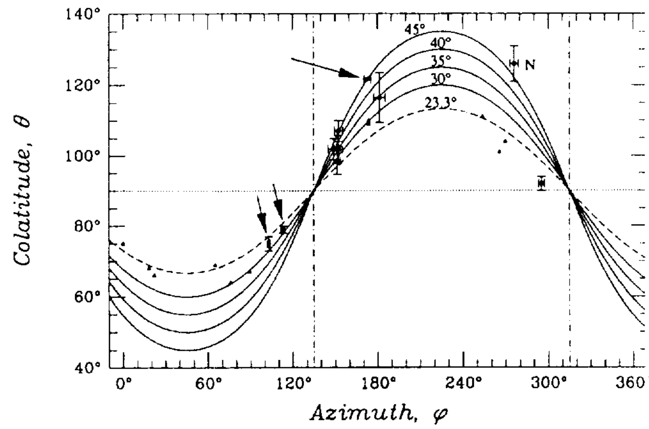


**Fig. 7.** Estimated source colatitude and azimuth (in the monopole antenna coordinate system) for all usable RMPR events listed in Table 1. The three highest-quality events are indicated by arrows, with the longest arrow at the near-perfect event. The point marked N is for Neptune; all the rest of the points with error bars are for Jupiter. A family of quasi-sinusoidal curves representing colatitude vs azimuth for incident rays lying within assumed E-planes having the indicated tilt angles are also plotted. The small triangular points without error bars represent the measurements by Lecacheux & Ortega-Molina (1987)

## 4. Full calibration based on all usable events

There were a number of RMPR events that occurred at greater distances from Jupiter from which some information is obtainable despite the fact that they were of poorer quality than the three above. For these poorer-quality events the measurement error had become so large due to the increased distance from the planet that the source could be assumed to be located at the center of the planet without appreciably increasing the error. (This was the case for *all* the measurements made for the L O-M paper.) The measurements for all our usable RMPR events are displayed in Fig. 7, with the three high-quality events that were considered in the previous section being indicated by arrows (the longest arrow for the near-perfect event). Each event provides one measurement of the antenna E-plane tilt, $\beta$, together with the colatitude and azimuth (in the $X_m Y_m Z_m$ coordinate system) the source point would have if it lay within this E-plane. The family of quasi-sinusoidal curves give colatitude vs azimuth for assumed E-planes having the indicated tilt angles (at 5° intervals). The vertical and horizontal error bar lengths represent mean errors due to the fact that measurements were made only at 48-sec intervals, rather than continuously. There are probably other sources of appreciable error that we cannot represent here. All of the points having error bars are for Jupiter except the one labeled "N", which we measured from an RMPR event during the Neptune encounter. The small triangles without error bars indicate the L O-M results, obtained from RMPR events at Saturn and Uranus. Unfortunately, insufficient information was provided in the L O-M paper for the determination of error bars for their measurements.

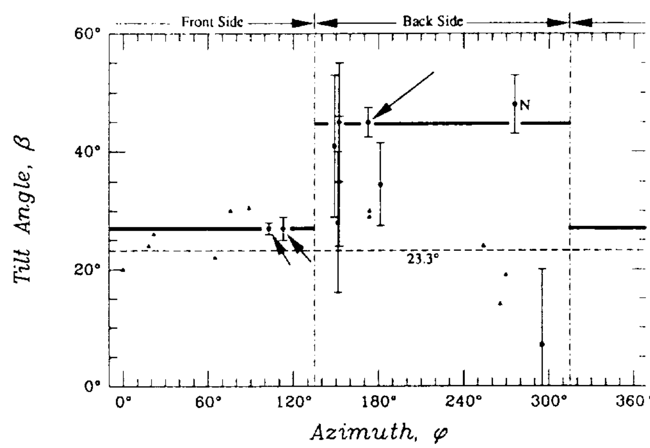


**Fig. 8.** Measured E-plane tilt angle plotted as a function of source azimuth for the RMPR events of the previous figure. The composite E-surface is approximated here by two half-planes, one with tilt angle of 27° for sources on the front side of the monopole plane, and the other with a 45° tilt for sources to the rear, as indicated by the two horizontal heavy lines

The data associated with all our RMPR events from which the measured points in Fig. 7 were derived are summarized in Table 1. In this table, *V1* and *V2* indicate Voyagers 1 or 2; *HOM* is hectometric or combined hectometric-kilometric radiation from Jupiter; *NKR* represents kilometric radiation from Neptune; *SCET* is spacecraft event time (i.e., UT at the spacecraft); *Dist* is distance from the center of the planet to the spacecraft in planetary radii ($R_J$ and $R_N$ for Jupiter and Neptune, respectively); $\varphi$ and $\theta$ are the azimuth and colatitude in the monopole coordinate system $[X_m, Y_m, Z_m]$; and $\beta$ is the tilt angle of the equivalent E-plane with respect to the monopole plane.

If the Voyager PRA antenna had been an isolated orthogonal pair of short dipoles, it would have possessed an E-plane with a tilt angle that would be independent of the direction of the radiation source used to measure it. It is clear from Fig. 7, however, that the Voyager PRA antenna does not have such a unique E-plane. Significantly different values of $\beta$ can occur for different azimuths of the source. We attribute this to the effect of the highly irregular conducting surface of the spacecraft and

**Table 1.** The RMPR events used in the study. Entries marked with † are measurement based on source location

| S/C | Source | Year/Day | SCET (hh:mm) | Dist ($R_P$) | $\varphi(°)$ | $\theta(°)$ | $\beta(°)$ |
|---|---|---|---|---|---|---|---|
| V1 | HOM | 1979/062 | 18:49.8 | 35.3 | 117.7±5.0 | 77.1±4.0 | 36.0±2.0 |
| | | | 18:49.8† | 35.3 | 113.0±1.5 | 79.0±1.0 | 27.0±2.0 |
| V1 | HOM | 1979/065 | 03:06.2 | 15.5 | 172.7±1.0 | 130.2±2.0 | 56.0±2.5 |
| | | | 03:06.2† | 15.5 | 173.0±2.5 | 121.7±1.0 | 45.0±2.5 |
| V1 | HOM | 1979/067 | 18:00.0 | 60.3 | 104.9±5.0 | 73.1±4.0 | 30.5±1.5 |
| | | | 18:00.0† | 60.3 | 103.0±1.0 | 75.0±2.0 | 27.0±1.0 |
| | | | 18:36.6 | 60.7 | 152.5±3.0 | 107.1±3.0 | 45.0±10.0 |
| V1 | HOM | 1979/069 | 15:23.4 | 89.3 | 152.3±3.0 | 101.8±4.0 | 35.0±11.0 |
| | | | 12:55.2 | 131.7 | 149.0±4.0 | 101.9±3.0 | 41.0±12.0 |
| | | | 03:49.2 | 140.7 | 151.5±2.5 | 98.6±4.0 | 28.0±12.0 |
| V1 | HOM | 1979/096 | 03:06.6 | 456.3 | 295.3±2.0 | 91.9±2.0 | 7.0±13.0 |
| V2 | HOM | 1979/195 | 23:18.6 | 72.5 | 181.5±4.0 | 116.5±7.0 | 34.5±7.0 |
| V2 | NKR | 1989/237 | 10:03.0 | 16.8 | 276±3.0 | 126±5.0 | 48.0±5.0 |

its various projecting members. In Fig. 7, the two nodal points in the family of quasi-sinusoidal curves are located at the $(\theta, \varphi)$ points (90°, 135°) and (90°, 315°), i.e., in the two directions of sources lying in the plane of the orthogonal monopoles. The front side of the antenna system, which is the side for which both $Z_m$ and $Z$ in Fig. 1 are positive, lies between the nodal points in the region for which $\theta < 90°$ in Fig. 7; the back side is the $\theta > 90°$ region. In Fig. 8, we have plotted the same $\beta$ values that appear in Fig. 7 as a function of azimuth, $\varphi$. Here again, the three points calculated from the three relatively high-quality RMPR events are indicated by arrows, with the longest arrow indicating the near-perfect event. The point marked N is for data obtained during Neptune encounter; it is the only one of our points that is not for Jupiter. We rank point N as the fourth-highest in quality. Our conclusions are drawn almost entirely from these four points.

We now assume that the antenna does not have an E-surface that is a single tilted plane. We approximate this surface by two half-planes of different tilt angles intersecting along the $X$ axis, one for sources on the front side of the monopole plane and the other for sources to the rear, as depicted in Fig. 1 (the front and rear half-planes are indicated by solid rather than dashed lines). The two horizontal heavy lines in Fig. 8 represent our best estimate of the tilt angle of the E-surface as a function of azimuth, $\varphi$. The two tilt angles obtained in this way are $\beta_f = 27°$ and $\beta_b = 45°$ for sources on the front and back sides of the antenna, respectively. The L O-M value of the tilt angle for all azimuths is 23.°3; it is indicated by the horizontal dotted line. Our value $\beta_f$ for the front side is in reasonable agreement with the L O-M value but our $\beta_b$ for the back side differs from the L O-M value by 21°. Our $\beta_b$ agrees more closely with the value calculated from Sayre's numerical model of the antenna-spacecraft system than with the L O-M value; however the Sayre E-plane tilt, unlike ours, appeared to be about the same at all azimuths. We point out that our bent E-plane model is at best a very rough approximation. The actual E surface dividing the arrival directions for which the indicated polarization sense is correct from those for which it is reversed probably has a more complex shape than our bent E-plane.

## 5. Conclusions and discussion

We conclude that the PRA antenna E-surface is not a single plane — that its tilt can be significantly different at different azimuths. Our results indicate that there are certain azimuths at which the L O-M (Lecacheux Ortega-Molina) E-plane tilt angle of 23.°3 is in error by as much as 20°, although at other azimuths the L O-M tilt value appears reasonable. We believe that the error bars associated with our four best points in Fig. 8 (i.e., the three with arrows and the one marked N) are realistic. We are less sure that our two horizontal solid lines in the figure indicate the correct tilt angles at *all* azimuths, but they represent the best approximation we can make from the presently available data. It is our opinion that a significant amount of Voyager data exists for which the use of the L O-M E-plane tilt angle would lead to an incorrect interpretation of the polarization sense of the received radiation. There is also the possibility that when observed times of the reversal of the indicated polarization sense (as the true E-surface sweeps across a source) are employed to obtain information related to source direction, the assumption of the L O-M tilt value can sometimes lead to a grossly inaccurate result. In order to minimize the possibility of such errors we advise that the L O-M tilt of 23° (or our value of 27°) be used when the observed radiation is incident on the front of the monopole antenna plane, and that our tilt of 45° be used when the radiation arrives from the back side of this plane.

It is unfortunate that the quantity of suitable data was insufficient to yield more conclusive results on the variation of $\theta$ with $\varphi$ in Fig. 8. We searched all of the 48-sec-average Voyager data from Jupiter and Neptune in locating the usable RMPR events, and we believe no others exist in these two data sets that meet our requirements (as listed on Sect. 3.1). However, some of the Jovian events which we were forced to reject because the 48-sec sampling rate did not provide sufficient time resolution could perhaps be salvaged if the same data sampled at 12 sec intervals (in both senses of apparent polarization) were available. Other sources of additional unused data (i.e., unused by us) are the Saturn PRA data sets obtained by the two Voyagers and the Uranus data set of Voyager 2. If additional points obtained from these unused data sets could be added to the plot of Fig. 8, the variation of E-surface tilt as a function of azimuth might be much better defined.

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